Frequency Use and Needs of Spaceborne Active Sensors

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ABSTRACT: *Spaceborne active sensors have been used for several years to study the Earth's surface and atmosphere. The intent of this paper is to present the unique types of sensors and their characteristics that determine their individual frequency needs; to present performance and interference criteria necessary for compatibility studies with other services in the frequency bands of interest; and to present a status of current frequency spectrum use and needs and compatibility studies of spaceborne active sensors and other services, along with any issues or concerns.*

1 INTRODUCTION

The purpose of this paper is to describe the radio spectrum frequency use and needs of the spaceborne active sensors, and in particular, those EESS (active) sensors used in the monitoring of the Earth's surface and atmosphere.

The intent is to present the unique types of sensors and their characteristics which determine their individual frequency needs; to present performance and interference criteria necessary for compatibility studies with other services in the frequency bands of interest; to present a status of current use and needs of the frequency spectrum and compatibility studies of spaceborne active sensors and other services, along with any issues or concerns.

2 ACTIVE SENSOR TYPES

There are five key active spaceborne sensor types:

a) SYNTHETIC APERTURE RADARS - Sensors looking to one side of the nadir track, collecting a phase and time history of the coherent radar echo from which typically can be produced a radar image or interferometric topographical map of the Earth's surface;

b) ALTIMETERS - Sensors looking at nadir, measuring the precise time between a transmit event and receive event, to extract the precise altitude of the Earth's ocean surface;

c) SCATTEROMETERS - Sensors looking at various aspects to the sides of the nadir track, using the measurement of the return echo power variation with aspect angle to determine the wind direction and speed on the Earth's ocean surface;

d) PRECIPITATION RADARS - Sensors scanning perpendicular to nadir track, measuring the radar echo from rainfall, to determine the rainfall rate over the Earth's surface concentrating on the tropics;

e) CLOUD PROFILE RADARS - Sensors looking at nadir, measuring the radar echo return from clouds, to determine the cloud reflectivity profile over the Earth's surface.

3 ACTIVE SENSOR CHARACTERISTICS

The characteristics of the five key types of active spaceborne sensors are summarized in Table 1. Viewing geometry describes the field of view of the active sensor. Footprint/dynamics gives the nature of the sensor footprint and whether it is fixed or scanning. The antenna beam characteristic gives details on the nature of the beamwidth of the sensor antenna. The radiated peak power gives either the peak power or a range of possible peak powers for each type of active sensor. The waveform characteristic describes the nature of the transmitted pulses. Spectrum width describes the bandwidth of the active sensor. The duty factor gives the percentage of time that the active sensor is transmitting. The service area characteristic gives the general geographical service area for each active sensor type.

3.1 Synthetic Aperture Radars

Synthetic aperture radars provide radar images or interferometric maps of the Earth's surface. The choice of RF center frequency depends on the Earth's surface interaction with the EM field. The RF bandwidth affects the resolution of the image pixels. The range resolution is equal to $c/2 / (BW \sin \theta)$, where c is the velocity of light, BW is the RF bandwidth, and θ is the incidence angle. To obtain a 1 meter range resolution at 30 degree incidence angle, for instance, the RF bandwidth should be 300 MHz.

Many SARs illuminate the swath off to one side of the velocity vector. Any interference sources within the illuminated swath area will be returned to the SAR receiver. The allowable image pixel quality degradation determines the allowable interference level.

3.2 Altimeters

Altimeters provide the altitude of the Earth's ocean surface. The choice of RF center frequency depends on the ocean surface interaction with the EM field. Dual frequency operation allows ionospheric delay compensation. For instance, TOPEX/POSEIDON uses frequencies around 13.6 GHz and 5.3 GHz. The wide RF bandwidth affects the height measurement accuracy. The time difference accuracy Δt is inversely proportional to BW, where BW is the RF bandwidth. The allowable height accuracy degradation determines the allowable interference level.

Table 1 - Active Spaceborne Sensor Characteristics

Characteristics	Sensor Types				
	SAR	Altimeter	Scatterometer	Precipitation Radar	Cloud Radar
Viewing Geometry	Side-looking @20-55 deg off nadir	Nadir-looking	(1) Six fan beams in azimuth (2) Two conical scanning beams	Nadir-looking	Nadir-looking
Footprint/ Dynamics	(1) Fixed to one side (2) ScanSAR	Fixed at nadir	(1) Fixed in azimuth (2) Scanning	Scanning across nadir track	Fixed at nadir
Antenna Beam	Fan beam	Pencil beam	(1) Fan beams (2) Pencil beams	Pencil beam	Pencil beam
Radiated Peak Power	1500-8000 W	20 W	100-5000 W	600 W	1000-1500 W
Waveform	Linear FM pulses	Linear FM pulses	Interrupted CW or Short Pulses	Short pulses	Short pulses
Spectrum Width	20-300 MHz	320 MHz	5- 80 kHz	0.6 MHz	300 kHz
Duty Factor	1-5 %	46 %	31 %	2 %	1-14 %
Service Area	Land/coastal/ Ocean	Ocean/Ice	Ocean/Ice/Land	Land/Ocean	Land/Ocean

3.3 Scatterometers

Scatterometers provide the wind direction and speed over the Earth's ocean surface. The choice of RF center frequency depends on the ocean surface interaction with the EM field and its variation over aspect angle. NSCAT illuminates the Earth's surface at several different fixed aspect angles. The SEAWINDS scanning pencil beam illuminates scans at two different look angles from nadir, and scans 360 degrees about nadir in azimuth. The narrow RF signal bandwidth provides the needed measurement cell resolution. For NSCAT, only 2-15 kHz is needed for the 25 km resolution. The allowable wind speed accuracy degradation determines the allowable interference level.

3.4 Precipitation Radars

Precipitation radars provide the precipitation rate over the Earth's surface, typically concentrating on rainfall in the tropics. The choice of RF center frequency depends on the precipitation interaction with the EM field. The backscatter cross section of a spherical hydrometeor:

$$\sigma_b = \pi^5 |K_w|^2 D^6 / \lambda^4 \tag{1}$$

where $|K_w|^2$ is related to the refractive index of the drop's

Table 2 - Criteria for Performance and Interference

Sensor Type	I/N Criteria	Data Availability Criteria	
		Systematic	Random
Synthetic Aperture Radar	-6 dB	99 %	95 %
Altimeter	-3 dB	99 %	95 %
Scatterometer	-5 dB	99 %	95 %
Precipitation Radar	-10 dB	N/A	99.8 %
Cloud Profile Radar	-10 dB	99 %	95 %

water, D is the diameter of the drop, and λ is the wavelength of the radar. The backscatter increases as the fourth power of the RF frequency. The narrow RF signal bandwidth provides the needed measurement cell resolution. TRMM uses only 0.6 MHz RF bandwidth. The allowable minimum precipitation reflectivity degradation determines the allowable interference level.

3.5 Cloud Profile Radars

Cloud profile radars provide the three dimension profile of cloud reflectivity over the Earth's surface. The choice of RF center frequency depends on the ocean surface interaction with the EM field and its variation over aspect angle. Equation 2 gives the expression for the return power level of the clouds. As can be seen in this expression, the return power increases with the square of the RF frequency. In the case of small particles (Rayleigh regime), the return power increases as the frequency to the power of four since the ratio depends on the relative particle size with respect to the wavelength. The cloud profile radar antennas have very low sidelobes so as to isolate the cloud return from the higher surface return illuminated by the sidelobes. The narrow RF signal bandwidth provides the needed measurement cell resolution. The allowable reflectivity accuracy degradation determines the allowable interference level.

$$P(mW) = \frac{\pi^5 10^{-17} P_r(W) g^2 \tau(\mu s) \theta_t^2 (\text{deg}) \left|K_w\right|^2 Z_r(mm^5/m^3)}{6.75 \times 2^{14} (\ln 2) r_\delta^2(km) \lambda^2(cm) l^2 l_r} \qquad (2)$$

4 SENSOR INTERFERENCE AND PERFORMANCE CRITERIA

The criteria for performance and interference are shown below for the various types of active spaceborne sensors and are summarized in Table 2:

- SAR: 10% degradation of standard deviation of pixel power yields I/N=-6 dB with mitigating effects of processing
- Altimeter: 4% degradation in height noise yields I/N= -3 dB
- Scatterometer: Degradation in measurement of normalized radar backscatter coefficient with simulations of measurement scheme yields I/N= -5 dB
- Precipitation Radar: 7% increase in minimum rainfall rate yields I/N= -10 dB
- Cloud Radar: 10% degradation in minimum cloud reflectivity yields I/N= -10 dB

5 INTERFERENCE LEVELS

The characteristics of the various types of active spaceborne sensors as shown in Table 1 indicate that they vary significantly in peak transmit power level. Table 3 shows for each active sensor, the typical transmitted peak power, the power levels received at the Earth's surface and power density flux levels at the Earth's surface for some typical sensor configurations.

Table 3 - Typical Interference Levels at Earth's Surface

Parameter	Sensor Type				
	SAR	Altimeter	Scatterometer	Precipitation Radar	Cloud Radar
Radiated Power, W	1500	20	100	578	630
Antenna Gain, dB	36.4	43.3	34	47.7	63.4
Range, km	695	1344	1145	350	400
PFD, dB(W/m^2)	-59.67	-77.25	-78.17	-46.55	-31.64

6 COMPATIBILITY STUDIES

Compatibility studies have been performed in ITU-R JWP 7-8R and ITU WP 7C for many of the active spaceborne sensor frequency bands. Table 4 summarizes which frequency bands and which sensor types in those bands have been analyzed for compatibility.

7 CURRENT STATUS

7.1 420 - 470 MHz

Resolution 712, Resolves 2 considers the provision of up to 6 MHz in the frequency range 420-470 MHz for active spaceborne sensors to monitor the forests at a spatial resolution of about 100m. The purpose of the allocation would be measurement of tropical biomass as requested by the U. N. environmental conference (UNCED) in 1992. For higher resolution missions, 10 to 40 MHz would be required; the band 430-440 MHz is considered to be the best option for the 6 MHz bandwidth: compatibility here has not been established, but may be possible with operational measures.

7.2 1215-1300 MHz

Primary allocation was given to active spaceborne sensors at WRC-97 limited by footnotes S5.332 andS5.335, to prevent interference to the radiolocation service and other primary services and to not constrain the development of the radiolocation service; JWP 7-8R showed compatibility of active spaceborne sensors and radiolocation systems in this band, provided that certain sensors design parameters are selected to satisfy the terrestrial radar interference criteria. The sub-band 1270- 1295 MHz has also been selected for use by wind profilers. Co-frequency sharing between the two services can be difficult. Another nearby alternative band has been identified for wind profilers (1300-1375 MHz).

7.3 3100-3300 MHz

Secondary allocation was given to active spaceborne sensors at WRC-97. Problems were identified by JWP 7/8R for sharing with some types of future shipborne military radars. The interference is only from the radar to the SAR and not in the opposite direction.

7.4 5250-5460 MHz

Primary allocation was given to active spaceborne sensors at WRC-97 limited by footnotes S5.447D, S5.448A and S5.448B; JWP 7-8R showed compatibility of active spaceborne sensors and radiolocation systems in this band, provided that certain sensors design parameters are selected to satisfy the terrestrial radar interference criteria. Studies have indicated that wireless LAN systems such as Hiperlan can be compatible with active sensors given certain hypotheses on their characteristics. But these hypotheses may not be in line with the latest specification of these future systems. This issue will need careful monitoring. Additionally, an expansion of this allocation by 110 MHz is required to meet the needs of spaceborne radar altimeters and future SAR missions.

7.5 8550-8650 MHz

Primary allocation was given to active spaceborne sensors at WRC-97 limited by footnote S5.469A. JWP 7-8R showed compatibility of active spaceborne sensors and radiolocation systems in this band, provided that certain sensors design parameters are selected to satisfy the terrestrial radar interference criteria.

Table 4 - Compatibility Studies by Frequency Band and Sensor Type

Frequency Band (MHz)	Active Sensor Type				
	SAR	Altimeter	Scatterometer	Precipitation Radar	Cloud Radar
430-440	(F)				
1215-1300	SIR-C, JERS-1				
3100-3300	ALMAZ	RA2 (F)			
5150-5250	RADARSAT-2 (F)	TOPEX-2 (F)			
5250-5350	RADARSAT, ASAR, ERS1/2, ENVISAT ASAR(F)	TOPEX	ERS1/2, NSCAT (F), METOP ASCAT (F)		
5350-5470	RADARSAT-2 (F)	TOPEX-2 (F)			
8550-8650	(P)	(P)	(P)		
9500-9800	X-SAR	(P)	(P)		
9975-10025					
13250-13400		TOPEX	NSCAT, SEAWINDS	TRMM (F)	
13400-13750		TOPEX, ERS1/2	NSCAT, SEAWINDS,	TRMM (F)	
			ENVISAT RA-2 (F)		
17200-17300			(P)	(P)	
24050-24250				(P)	
35500-35600		(P)	(P)		
78000-79000					(P)
92000-95000					CLOUDSAT (F)
130000-131000		(P)			(P)
192000-195000					(P)
Note: (F) Future Proposed, (P) Postulated, and Currently Operating otherwise					

7.6 9500-9800 MHz

Primary allocation was given to active spaceborne sensors at WRC-97 limited by footnote S5.476A. JWP 7-8R showed compatibility of active spaceborne sensors and radiolocation systems in this band, provided that certain sensors design parameters are selected to satisfy the terrestrial radar interference criteria.

7.7 9.975-10.025 GHz

Secondary allocation was given to active spaceborne sensors under Footnote S5.479 for weather radars. No recent compatibility studies have been conducted in JWP 7-8R or WP 7C.

7.8 13.25-13.75 GHz

Primary allocation was given to active spaceborne sensors at WRC-97 limited by footnotes S5.498A, S5.501A and S5.501B. JWP 7-8R showed compatibility of active spaceborne sensors and radiolocation systems in this band.

7.9 17.2-17.3 GHz

Primary allocation was given to active spaceborne sensors at WRC-97 limited by footnote S5.513A. JWP 7-8R showed compatibility of active spaceborne sensors and radiolocation systems in this band.

7.10 24.05-24.25 GHz

Secondary allocation was given to active spaceborne sensors at WARC-97. The spectrum is intended for use by precipitation radars and scatterometers.

7.11 35.5-36 GHz

Primary allocation was given to active spaceborne sensors at WRC-97 limited by footnote S5.551A. JWP 7-8R showed compatibility of active spaceborne sensors and radiolocation systems in this band. JWP 7-8R concluded that a bandwidth of 500 MHz for active sensors around 35 GHz will meet the long term requirements for wideband altimetry.

7.12 78-79 GHz

Primary allocation is given to active spaceborne sensors by footnote S5.560. JWP 7-8R showed compatibility of active spaceborne sensors and radiolocation systems in this band. This band must be retained for spaceborne active sensors other than cloud radars.

7.13 - 94.0-94.1 GHz

Primary allocation was given to active spaceborne sensors, specifically cloud profile radars, at WRC-97 as specified in footnote S5.562. JWP 7-8R showed compatibility of active spaceborne sensors and radiolocation systems and radioastronomy in this band. In the 92-95 GHz frequency band, a draft new Recommendation recommended that spaceborne cloud radars be operated in the band, and that 100 MHz bandwidth is sufficient; it also recommended that CPRs and fixed and mobile services not share common frequency bands; also CPRs and the fixed satellite (Earth-to-space) service should not share common frequency bands. Methods have been identified recommended to be adopted to mitigate the potential impact to radioastronomy. Coordination is required with radioastronomy telescopes to avoid destructive main-to-main beam coupling.

7.14 - 130-131 GHz

Recent proposals have been submitted to study the possibility of using the 130-131 GHz band for wideband (1 GHz) altimetry and higher sensitivity (< -30 dBZ) cloud profile radars.

7.15 - 192-195 GHz

Recent proposals have been submitted to study the possibility of using the 192-195 GHz band for even higher sensitivity (< -40 dBZ) cloud profile radars.

8 ITU Recommendations and Resolutions concerning Active Spaceborne Sensors

There are several ITU recommendations and resolutions concerning active spaceborne sensors as listed in Table 5.

9 ISSUES/CONCERNS

The issues and concerns for active spaceborne sensors are summarized in Table 6.

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[4] Eli Brookner, Editor, "Aspects of Modern Radar", *Artech House*, Boston, 1988

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Table 5 – ITU Recommendations and Resolutions Concerning Active Spaceborne Sensors

Recom-men-dations/ Resolutions	Frequency Range	Title
SA.577-5	1215-1260 MHz	Preferred Frequencies and Necessary Bandwidths for Spaceborne (S/B)Active Remote Sensors
SA.1071	13.75-14.0 GHz	Use of the 13.75 to 14.0 GHz Band by the Space Science Services and the Fixed-Satellite Service
SA.1161-1	400 MHz -95 GHz	Performance and Interference Criteria For Active Spaceborne Sensors
SA.1260	410-470 MHz	Feasibility of Sharing Between Active S/B Sensors and Other Services in the Vicintiy of 410-470 MHz
SA.1261	92-95 GHz	Feasibility of Sharing Between Active S/B Cloud Radars and Other Services in the Range of 95-95 GHz
SA.1280	1-10 GHz	Selection of Active S/B Sensor Emission Characteristics to Mitigate the Potential for Interference to Terrestrial Radars Operating in Frequency Bands 1-10 GHz
SA.1281	13.4-13.75 GHz	Protection of Stations in the Radiolocation Service from Emissions from Active Spaceborne Sensors in the Band 13.4-13.75 GHz
SA.1282	1215-1300 MHz	Feasibility of Sharing Between Wind Profiler Radars and Active S/B Sensors in the Vicinity of 1260 MHz
SA.1347	1215-1260 MHz	Feasibility of Sharing Between Radionavigation-Satellite Service Receivers and the Earth Exploration-Satellite (Active) and Space Research (Active) Services in the 1215-1260 MHz Band
724	5250-5350 MHz	Use of the Frequency Band 5250-5350 MHz by Spaceborne Active Sensors
725	5350-5460 MHz	Use of the Frequency Band 5350-5460 MHz by Spaceborne Active Sensors
727	420-470 MHz	Use of the Frequency Band 420-470 MHz by the Earth Exploration-Satellite (Active) Service

Table 6 - Issues and Concerns for Active Spaceborne Sensors

Frequency Band, MHz	Issues/ Concerns
420-470	Preference of up to 40 MHz bandwidth for high resolution applications; however only 10 MHz bandwidth in 430-440 MHz band potentially available due to difficulties in sharing with fixed and mobile services in 420-430 MHz and 440-470 MHz ranges; sharing studies are underway between active spaceborne services in 430-440 MHz band and amateur services. Communication between spacecraft and astronauts is in the 410-420 MHz band.
1215-1300	The subband 1270-1295 MHz has been selected for use by wind profilers; sharing studies showed that with only a small number of compressed pulse wind profiler radars, they are not compatible with SARs in this band.
5250-5460	Studies have indicated that wireless LAN systems such as Hiperlan can be compatible with active sensors given certain hypotheses on their characteristics. But these hypotheses may not be in line with the latest specification of these future systems.
5460-5570	As possible extension band from the 5250-5350 MHz band spectrum for high resolution radar altimeters; TOPEX/ POSEIDON currently operates its second frequency with a 320 MHz bandwidth at 5.15-5.47 GHz.; the sharing scenario with NGSO FSS is difficult.
94000-94100	Protection needed of radio astronomy service in their 86-92 GHz band; recommended that technical and operational measures be adopted to minimize effects on radio astronomy operations; coordination is required with radio astronomy telescopes to avoid destructive main-to-main beam coupling
130000-131000	As possible band for wideband (1 GHz) altimeters and more sensitive (<-30 dBZ) cloud profile radars
192000-195000	As possible band for most sensitive (<-40 dBZ) cloud profile radars